elektrorevue
ISSN 1213 - 1539

Interactive energy saving automatic control of water supply pump

doc. Ing. O.Kiselychnyk, Ph.D., doc. Ing. J.Koláčný, CSc. , Ing. S.Buryan, Ph.D., Ing. T.Ondrák

National Technical University of Ukraine, FEA, Electrical Drives Department,
Peremogy Ave., 37, korp.20, 03056, Kiev-56, Ukraine
Phone +380442418656, **E-mail:** koi@gala.net , sburyan@voliacable.com

Technical University of Brno, Faculty of Electrical Engineering and Computer Science,
Department of Power Electrical and Electronics Engineering
Technicka 8, 61600 Brno, Czech Republic
Phone 4114-2699, **E-mail:** kolacny@feec.vutbr.cz, xondra11@stud.feec.vutbr.cz

The article is devoted to a novel approach to energy saving in water supply systems. The idea of interactivecontrol of the pump bases on consumers behavior during water consumption and is realized as some game of the systém and consumers. Fundamentals, simulation and technical realization of the controller are presented.

1. Introduction

It becomes the modern norm to implement squirrel cage induction motors fed by frequency converters for pump
driving. The opportunity of using these drives to organize electromechanical systems with energy efficient control algorithms has caused such a trend. The main solutions proposing by leading developers and researches may be divided into four directions [1, 2]:
- stabilization of pressure of dictating points;
- stabilization of reservoir levels;
- control of pump velocity (water flow, pressure) according to the graphics of day water consumption demands of consumers;
- extremal control system with automatic search of the pump working point with maximum possible efficiency for current water flow.

Two first directions actually mean control of pump velocity providing maximum possible reserve of water potential energy within water supply system. Such approach is most effective for the supply stations of the first or second water raising. But efficiency decreases due consumers demands being not taken into account in case of local systems of pressure increasing. These demands are formed beforehand as the result of experimental researches in the form of day graphics of pump technological parameters. They can be provided using closed or opened loop program control systems. The level of energy saving of such a system is defined by pump velocity reduction. 10% velocity reduction results in about 40% energy saving. But these graphics do not precisely describe necessary data and do not take into account all possible features of consumers behavior. This fact leaves some opportunity for future advancing. The extremal systems do not need any beforehand information about consumption demand. They provide more high level of energy efficiency. But their realization is too complicate and individual for every installation.

Objective of the work is to develop the interactive electromechanical control system of water supply pump, which could be able in real time scale to define consumers demands and to provide corresponding minimum enough velocity of the pump. This time energy efficiency

elektrorevue
ISSN 1213 - 1539

of the installation is higher compared with day demands graphics using. But it is lower than under extremal control. Technical realization of the system bases on using only standard equipment and it is simpler than in case of extremal control. This results in less expenses covering. The realization must be universal. The equipment developed for some pump must be used for another without hardware changing.

2. Energy saving control algorithm of water supply pump

The idea of the pump interactive control is explained by Fig.1. Reference signals of the water supply system are formed using indirect “asking” of consumers (periodical measuring of water flow). It means that system reference is defined by its load in automatic mode. If pump velocity has been decreased and consumers provide in fact water flow larger compared with calculated value, then pump velocity is increased proportionally to the ratio of real and calculated values. In opposite case the pump velocity is decreased. That way consumers automatically define minimum enough velocity to satisfy their demands. If there is no reaction of consumers on water flow changing, then the velocity is fixedly decreased.

Let us consider the interactive control algorithm in detail. After start the working point of the pump installation is A.

After some fixed time T0 has flown, the pump velocity is decreased from ω_1 value to ω_2. Theoretically the following working point must be B. The calculated value of water flow after velocity decreasing is

$$Q_{cal} = Q_B = Q_A \frac{\omega_2}{\omega_1}. \tag{1}$$

But consumers dependently on water flow demands remove the working point. In this example it is into right and the working point is C (removing is shown by dotted curve from A to C). The value of real water flow is $Q_{Real}=Q_C$. After time T0 the velocity is changed according to equation

$$\omega_3 = \omega_2 \frac{Q_{Real}}{Q_{Cal}} = \omega_2 \frac{Q_C}{Q_B} = \omega_1 \frac{Q_C}{Q_A}. \tag{2}$$

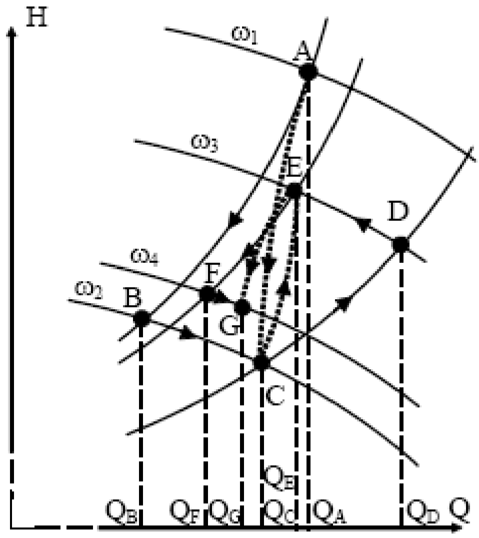


Fig.1. Pump characteristics under interactive energy saving control

The next theoretical working point must be D. Consumers dependently on their demands can remove it to another position, for example E. After time T0 the pump velocity must be as follows

$$\omega_4 = \omega_3 \frac{Q_{Real}}{Q_{Cal}} = \omega_3 \frac{Q_E}{Q_D} = \omega_2 \frac{Q_E}{Q_C}. \tag{3}$$

elektrorevue
ISSN 1213 - 1539

Further processes are repeated.

3. Mathematical formalization of energy saving algorithm

The block diagram of the controller realizing the proposed algorithm is shown in Fig.2.

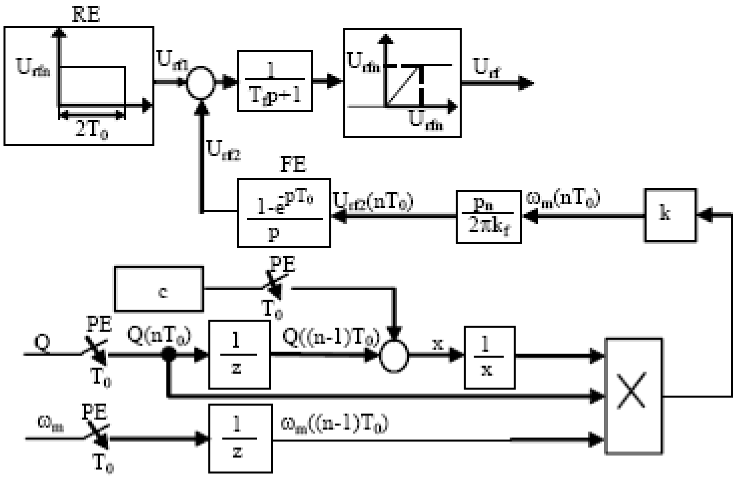


Fig.2. The block diagram of the energy saving algorithm

The reference element RE forms the voltage reference Urf1 of frequency converter. This reference is correspondent to the nominal value of the motor frequency. It remains constant during time interval $2T_0$. Sample time T0 must exceed transient time of the system caused by step changing of the frequency voltage reference.

Information about productivity of the pump Q and motor velocity ωm is delivered into the algorithm at fixed moments of time nT_0 (n – positive integer) by pulse elements PE. The desirable value of motor velocity within the every following step of the algorithm is defined by equation

$$\omega_m(nT_0) = \frac{kQ(nT_0)}{Q((n-1)T_0) + c}\,\omega_m((n-1)T_0), \qquad (4)$$

where k is a positive coefficient slightly less than one; c – small positive constant to prevent division by zero.

The coefficient k is necessary to provide workability of the algorithm under condition of no reaction of consumers onvelocity changing (actually if $Q(nT_0)=Q((n-1)T_0)$). Using of k slightly redefines the algorithm but simplifies greatly itstechnical realization.

The frequency voltage reference is

$$U_{rf2}(nT_0) = \frac{p_n}{2\pi k_f}\,\omega_m(nT_0), \qquad (5)$$

where p_n- motor poles pairs number; k_f – transfer coefficient of the frequency converter.

The forming element FE converts the discrete signal of U_{rf2} into analogous signal. Links 1/z realize signal delay per sample time.

Zero beginning conditions of system work ($Q=0$, $\omega_m=0$) cause that voltage U_{rf2} remains zero during time interval $2T_0$. Then the value of the frequency voltage reference U_{rf} will be defined only by voltage U_{rf1}. After that time reference U_{rf} will be defined only by voltage U_{rf2}.

To decrease motor current during transients the voltage reference is transmitted through the aperiodical filter with timeconstant T_f.

If the mechanical characteristic of the motor is hard enough the control algorithm can be greatly simplified. In this case it is possible to use information about frequency voltage

elektrorevue
ISSN 1213 - 1539

reference instead of velocity (it is not necessary to use velocity sensor). The ramp of the frequency converter can be use also instead of the filter.

The algorithm is the next

$$U_{rf2}(nT_0) = \frac{kQ(nT_0)}{Q((n-1)T_0)+c} U_{rf2}((n-1)T_0). \tag{6}$$

The block diagram of the simplified controller is highlighted in Fig.3. It is possible in the algorithm additionally to limit maximum and minimum values of frequency reference voltage.

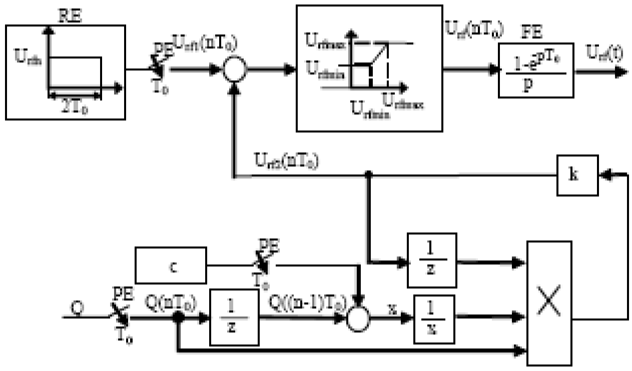


Fig.3. The block diagram of the simplified interactive energy saving algorithm

4. Mathematical model of energy saving interactive control system of pump

The block diagram of the system is shown in Fig.4.

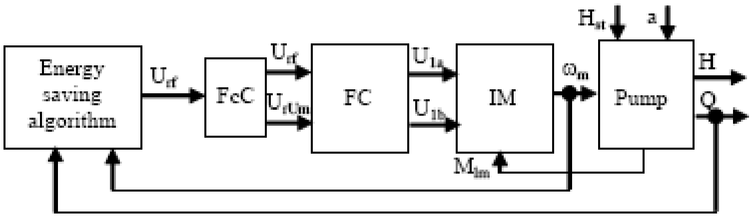


Fig.4. The block diagram of the interactive automatic control system of pump

Functional converter FcC using the output signal of the energy saving algorithm forms the reference of voltage amplitude U_{rUm}. The dependence of U_{rf} and U_{rUM} is chosen in such a way that the frequency converter FC provides steady state ventilator dependence of output voltage frequency f and amplitude U_m. Such dependence makes possible to decrease the critical torque of the induction motor IM in case of frequency decreasing. This approach provides smoothness of pump control.

The block diagram of FcC is presented in Fig.5, where k_{Um} – amplitude transfer coefficient of FC.

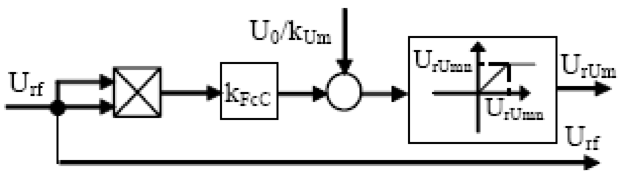


Fig.5. The block diagram of FcC

The transfer coefficient of FcC

$$k_{FcC} = \frac{U_{mn} - U_0}{f_n^2} \frac{k_f^2}{k_{Um}}, \tag{7}$$

where f_n – nominal frequency; U_{mn} – nominal amplitude.

The voltage U_0 is used to increase load ability of the motor in case of frequency is small. The value of U_0 is chosen about 6÷25% of nominal value.

elektrorevue
ISSN 1213 - 1539

The mathematical model of FC bases on the equations of three phase symmetrical sinusoidal voltage system and transformation 3-2 [3]

$$
\begin{aligned}
&U_A = U_m \sin\Theta;\\
&U_B = U_m \sin(\Theta - 2\pi/3);\\
&U_C = U_m \sin(\Theta + 2\pi/3);\\
&\Theta = 2\pi\int_0^t f dt;\\
&U_{1a} = 3U_A/2;\\
&U_{1b} = \sqrt{3}(U_B - U_C)/2,
\end{aligned}
\tag{8}
$$

where U_A, U_B, U_C – voltages of correspondent stator phase; Θ - electrical angle; U_{1a}, U_{1b} – a and b components of stator voltage vector within stationary coordinate system of the stator.

Transients of FC are approximated by aperiodical links

$$
\begin{aligned}
&f = \frac{k_f}{T_{\mu 1}p+1}U_{rf};\\
&U_m = \frac{k_{Um}}{T_{\mu 2}p+1}U_{rUm},
\end{aligned}
\tag{9}
$$

where $T_{\mu 1}$, $T_{\mu 2}$ – small time constants.

The two phase model within stator coordinate system a-b [3] is used to describe squirrel cage induction motor.

Let us take that cross sections of input and output pipes of the pump are equal. Then complicate transients in pump and pipe net may be approximated by aperiodical link. The differential equation describing the pump under velocity control is the following [4]

$$
\frac{m}{\rho g}\dot{Q} + s^2(a + a_f)Q^2 = s^2\frac{H_{0n}}{\omega_n^2}\omega^2 - s^2 H_{st}, \tag{10}
$$

where H_{st} – value of static pressure; H_{0n} – fictitious pump pressure with nominal velocity and zero productivity; a – hydraulic net resistance; a_f – hydraulic pump resistance; ρ - water density; g – gravitation acceleration; m – water mass in pump and pipe net.

Pressure and power of the pump [4]

$$
\begin{aligned}
&H = H_{0n}(\omega/\omega_n)^2 - a_f Q^2;\\
&P = \rho g Q H/\eta,
\end{aligned}
\tag{11}
$$

where η - pump efficiency (is accepted as nominal for the research).

Pump velocity and motor load torque

$$
\begin{aligned}
&\omega = \omega_m/i_n;\\
&M_{1m} = P/\omega_m,
\end{aligned}
\tag{12}
$$

where i_n – transfer coefficient.

5. Simulation of the interactive energy saving control system of the pump

The research has been carried out for the system based on vertical multilevel centrifugal pump CV 125-30 with the rated power 90kWt [5]. Other parameters were Q_n=125 m3/hour, H_n=175 m, η_n=76%, H_{0n}=212 m, ω_n=216 rad/s, a_f=0.002368 m/(m^6/hour^2), s=1 m^2, H_{st}=20 m. The following squirrel cage motor has been chosen for investigation 4A250M2Y3 [6]. Its nominal parameters were P_{2n}=90 kWt; n_0=3000 rot/min (p_n=1); U_{1p}=220 V; f_n=50 Hz; η=0,92; cosφ=0,9; xμ=5,2 rel. val.; $R_1^{/}$=0,02 rel. val.; $x_1^{/}$=0,078 rel. val.; $R_2^{//}$=0,016 rel. val.; $x_2^{//}$=0,13 rel. val.; m_n=1,2; m_M=1; m_k=2,5; s_n=0,014; s_k=0,1; J=0,52 kgm^2. The parameters of FC and

elektrorevue
ISSN 1213 - 1539

FcC were accepted as follows k_f=5 Hz/V, k_{Um}=31 V/V, $T_{\mu 1}=T_{\mu 2}$=0.01 s, U_{rUm}=6.67 V, U_0=31 V, k_{FcC}=0.135 1/V.

The sum inertia of the motor was accepted equal to motor inertia to simplify research procedure. The value of m was chosen 10000 kg to make calculation time less. In this case transients time caused by ωm changing did not exceed 3 s.

The energy saving algorithm runs with following parameters data U_{rfn}=10 V, T_0=10 s, T_f=0.1 s, k=0.95, c=10^{-8}.

The result of the system research is shown in Fig.6 and 7. During time $2T_0$ the system is started into the beginning working point A with hydraulic resistance a=0.0105 m/(m^6/hour^2).

At the moment of time 20 s the pump velocity is decreased on 5%. At 20.5 s consumers decrease net resistance a for a 0.0018 m/(m^6/hour^2) increasing pump productivity to desirable value. The working point moves from A to C. At the next step, when t=30 s, velocity is increased. After 0.5 s has flown, consumers increase hydraulic resistance for a 0.001 m/(m^6/hour^2) decreasing pump productivity to the desired value. The working point is E. Further, when time equals 40 s, the pump velocity is decreasing again. After 0.5 s consumers decrease resistance for a 0.002 m/(m^6/hour^2). The new working point is G. In such a way consumers personally define minimum enough pump velocity to satisfy their demands in desired water flow.

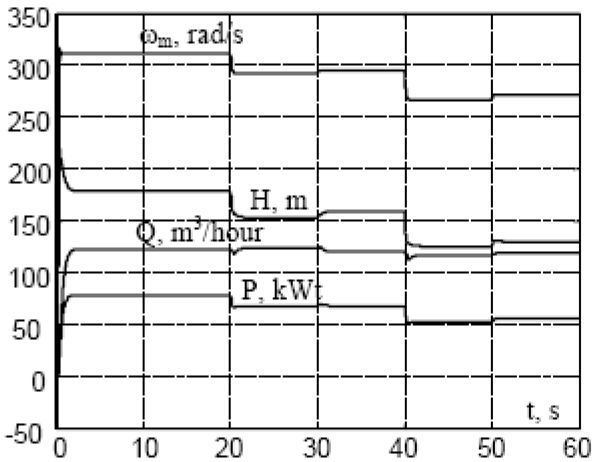


Fig.6. Transients of the control systém

The case, if consumers from the start do not react on velocity changing, is shown in Fig.8. The analogous picture will be in case of no consumers reaction starting with any working point of the pump.

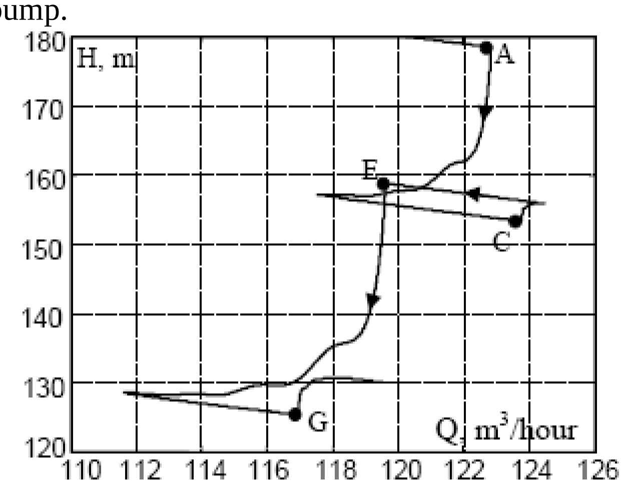


Fig.7. Pump characteristics under control process

elektrorevue
ISSN 1213 - 1539

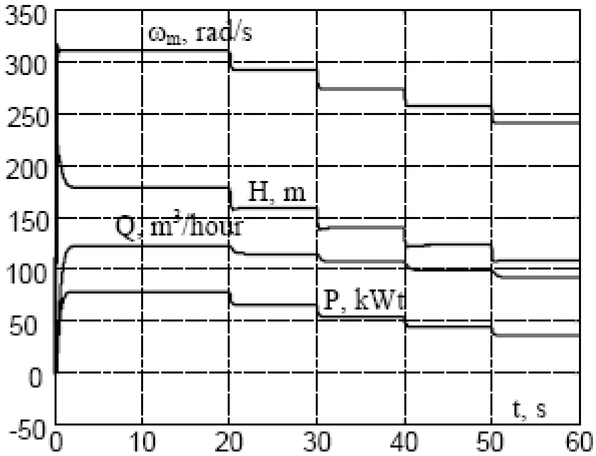


Fig.8. Control system transients without consumers reaction on velocity changing

It has been researched transients of the system (Fig.4), where pressure PI-controller was used instead of the energy saving algorithm, to evaluate energy efficiency of the developed system. Transfer coefficient of proportional part and time constant of integral part of the PI-controller equaled one. 10 V limits of controller output and integral part output were taken into account. Pressure feedback gain was 0.047 V/m. Pressure was stabilized at the level of 178.5 m. It corresponded to the pressure of interactive system during 0-20 s. Reaction of consumers was simulated in a such way to provide the same pump productivity as shown in Fig.6 for correspondent time intervals. The power consumed during research time in the stabilization system was 1.25 kWt·hour. This power in the developed system was 1.1 kWt·hour. The energy saving was 0.15 kWt·hour or 12%.

6. Description of hybrid experimental unit

Fig.9 shows experimental sample of the interactive controller based on Fig.3. It is realized based on ATmega 8535 microcontroller [7], DAC TLC5615C, three elements seven segments led indicator RL – T3620 SBAW/D15.

The controller is fed by +5 V DC stabilized voltage supply. The output voltage of the water flow sensor must be in the range 0 – 2.56 V. The output voltage of the controller (frequency converter reference) may vary from 0 to 5.12 V. Using of four buttons gives the following choice of indication modes:

- input voltage of the controller indication (voltage of the water flow sensor mounted on pump output);
- output voltage of controller indication;
- indication, increasing, decreasing and remembering of values of sample time T_0 (from 15 s till 1485 s discretely every 15 s), k coefficient (from 0.8 till 0.99), U_{rfmin} (from 0 to 3.5 V), U_{rfmax} (from 3.9 to 5.2 V).

elektrorevue
ISSN 1213 - 1539

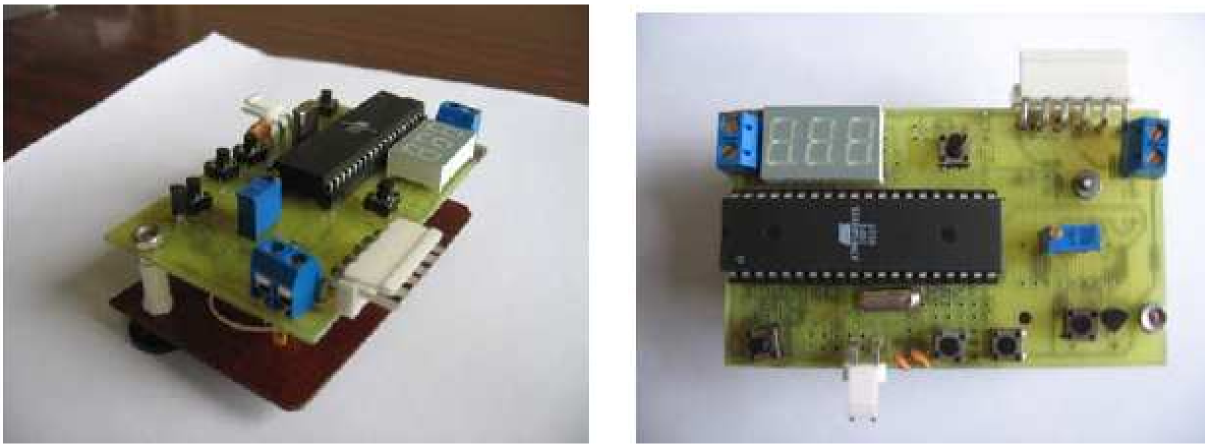
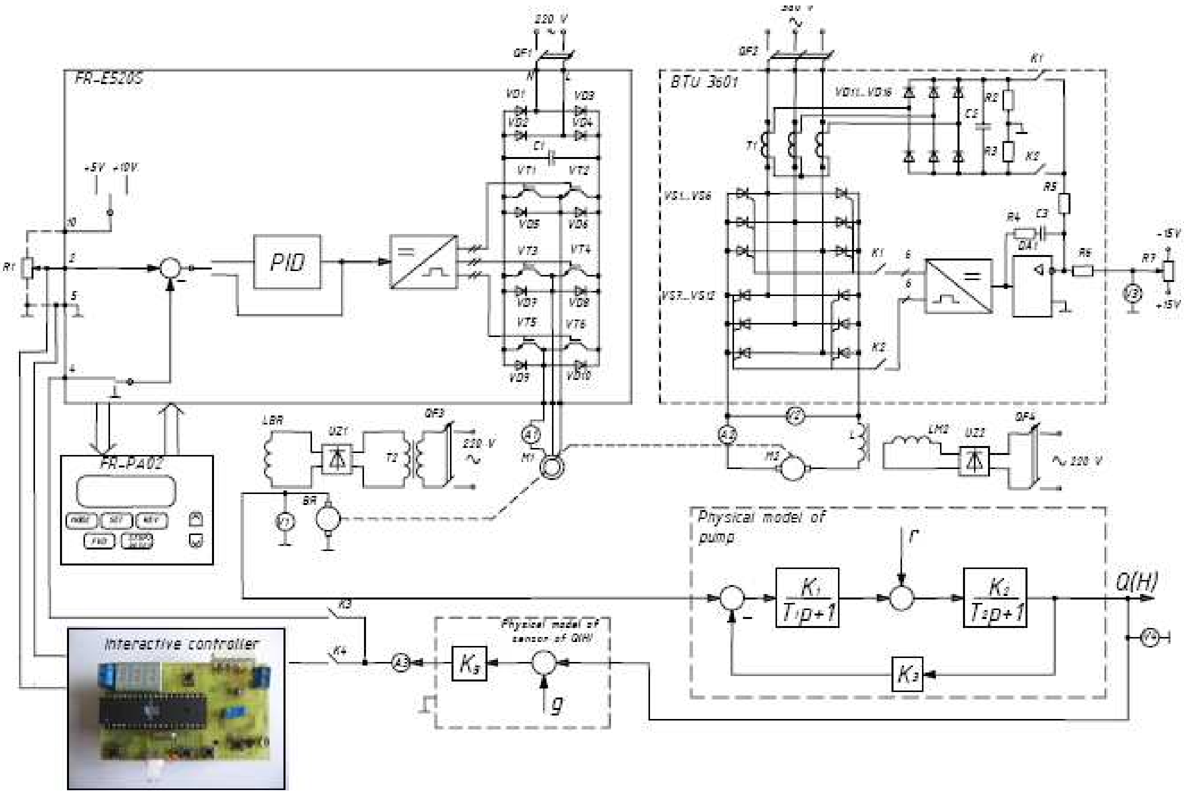


Fig.9. Experimental sample of the interactive controller

Software was developed using AVR Studio 4.12 environment and programmed through Starter Kit STK500.



The special testing unit was developed to carry out research. The functional electrical scheme of the unit is shown in Fig.10. The view of the unit is presented in Fig.11.

Fig.10. The functional electrical scheme of the testing unit

elektrorevue
ISSN 1213 - 1539


Fig.11. The view of the testing unit

Mitsubishi transistor frequency converter FR–E520S with rated power 0.75 kWt is used for unit organizing. It includes embedded ramp, PID-controller, choice of frequency or vector motor control. Frequency reference is delivered from analogous input 2 or from the control panel FR–PA02. The model of the pump is realized as aperiodical link of second order by circuitry board based on operational amplifiers. The unit gives an opportunity to tune transfer coefficients, time constants of the pump model and also values of r disturbance. It is possible to indicate the output and intermediate signals of the model using voltmeters and scope. This circuitry board includes also the model of the technological parameter sensor (water flow) with voltage output (0-10 V) or current output (0-20mA). There is a possibility to create nonzero beginning signal corresponding to zero value of parameters. It was developed the controlled torque source based on BTU 3601 standard DC drive to simulate motor load torque. The pair of electrical machines is connected to the unit (induction motor AOL-11-4 with rated power 0.6 kWt, DC motor G-11 with rated power 0.8 kWt). Micromachine SL-261 is used as velocity sensor.

7. Research of operation of the interactive energy saving controller

The research has been carried out with limits of controller output voltage from 1 to 5.1 V, k=0.99, T_0=15 s. The parameters of the pump model were chosen in such a way that the output voltage of the sensor 2.56 V was correspondent to the maximum velocity and transients were aperiodical. Increasing of r value means decreasing of hydraulic resistance of the net. Decreasing of r – vice versa. The research has proved workability of the proposed interactive controller as for the vector motor control and for the frequency motor control (U/f=const, U/f_2=const).

In case of no consumers reaction on pump velocity changing (r=const and no changing of R7 position) the motor runs to maximum velocity with f=50 Hz. Then the velocity is decreasing for a 1% relatively of the previous value every 15 s. The frequency was 10Hz when the lower output limit was reached. The further decreasing of the pump velocity is possible only with decreasing of the lower limit of the output voltage of the controller. If there is hydraulic resistance decreasing during the sample time, then velocity reduction fulfills according equation (6) more faster compared with no consumers reaction.

If there is dash increasing of hydraulic resistance during sample time, then the minimum possible motor voltage frequency will be provided next sample time. If hydraulic resistance is decreasing and input controller voltage is higher than its previous value taking into consideration k ($kQ(nT_0)>Q((n-1)T_0)$), then velocity will be increasing. If there is no reaction of consumers in this case and inequality above is correct, then velocity will be increasing further. If the pump is rotated with low velocity, then even slightly decreasing of hydraulic net resistance results in maximum possible velocity next step. The research has

elektrorevue
ISSN 1213 - 1539

been conducted without motor load torque and with double rated load torque. Arbitrary changing of r and load torque during sample times does not affect system stability because of coordinates measurement takes place at fixed times and the sample time is enough transients to be finished.

If pump velocity is about of its nominal value taking into account very hard character of mechanical characteristic of the motor, productivity Q is decreased for about 0.4% while load torque is changing from 0 to double nominal value. This little changing of Q is enough for foreseen reaction of the interactive controller. If frequency is low (10 Hz), the mechanical characteristic of the motor is softer. Then productivity decreasing is 65%. Thus the interactive controller is sensitive even to little load torque changing.

Changing of r and motor load torque is interconnected for real pumps [4]. Therefore it is obligatory to define more exactly results and dependences above using real physical model of the pump installation.

If pump velocity is maximum possible and hydraulic resistance is minimum possible, then the velocity can be only decreased. In this case consumers have to increase temporary hydraulic net resistance and then return it to minimum possible value for providing necessary water flow (velocity is maximum possible).

Decreasing of k results in dasher periodical decreasing of velocity. But this makes lower sensitivity of the controller to hydraulic net resistance decreasing under necessity of velocity increasing.

Changing of interactive controller parameters (upper and lower limits of output voltage, sample time, k) and indication modes during system running do not affect its stability and workability.

8. Conclusion

The developed algorithm of interactive control of pump installation gives a possibility of considerable energy saving in water supply systems. Technical realization of the algorithm bases on using mainly standard equipment. The developed interactive controller is universal for any pump installation.

This paper has been supported by Grant project MSM 0021630516.

References

[1] B.S.Leznov "Energy saving in pump installations". –Moscow: Energoatomizdat, 1991. -144 pp. (in Russian)

[2] O.Kiselychnyk, J.Kolacny, M.Ostroverkhov, P.Hapal/ Neural networks application for energy saving extremal
control of water supply pump / Elektrorevue, Czech Republic, (http://www.elektrorevue.cz), 2006, vol. 06027, no. 6, p. 1-7. ISSN: 1213-1539. (in English and Czech)

[3] Theory of electrical drive: Handbook/ M.G.Popovich, M.G.Borisyuk, V.A.Havrilyuk and others. –Kiev: Vyshcha shkola, 1993. -494 pp. (in Ukrainian)

[4] Popovich M.G., Kiselychnyk O.I./ Passivity principle based electromechanical automatic control systems of
turbomechanisms working parameters / Automated drives problems. News of National Technical University "Kharkiv Polytechnic Institute". N43. –Kharkiv, NTU KhPI, 2004. pp.16-19. (in Ukrainian)

[5] Grundfos – WinCAPS version 7.41, CD.

[6] Induction motors of 4A type/ A.E.Kravchik, M.M.Shlaf, V.I.Afonin, E.A.Sobolenskaya. –Moscow: Energoizdat, 1982. -504 pp. (in Russian)

[7] Baranov V.N. Application of AVR microcontrollers: schemes, algorithms, programs. Second edition. Dodeka XXI [M.], 288 pp. 2006 (in Russian)